Validation Study of the Use of Matlab/Simulink Synchronous-Machine Block for Accurate Power-Plant Stability Studies

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I. INTRODUCTION

Power system simulation by means of simulation tools is, nowadays, very important on research and development of new technologies. In the last years, the simulation of power systems through software applications has been an active research topic, and it has achieved an essential role in electrical engineering panorama, for instance in network stability studies and protective devices coordination studies.

The stability of an interconnected power system is its ability to return to normal or stable operation after having been subjected to some form of disturbance. With interconnected systems continually growing in size and complexity, it is becoming increasingly more difficult to maintain synchronism between various parts of a power system [1]. The simulation of power systems provides very useful information about stability of the network, and allows researchers to test the system behavior against disturbances that cannot be tested in real grids [2].

A protection coordination study analyzes the impact of short-circuits and equipment failures within a power system and determines the effects on the operation of the system. In a properly coordinated system, the protective relays are selected and set to minimize the impact of electrical equipment failures. The goal of a coordination study is to achieve an optimum balance between equipment protection and selective isolation that is consistent with the operating requirements and the reliability of the overall power system [3].

It is obvious that an accurate simulation of the power system performance in several functioning situations can simplify the protective system design and its coordination study. Even more, taking into consideration that most electrical power systems are not planned with protective device on mind, but are designed for minimum losses or minimum upfront investment.

Nowadays there are several software for power system simulation, such as ATP, Simsen, PSS/E, PSCAD or Matlab, which are commercially available. They have a great potential on research, and on education for power systems operation and stability [4]. Other active research topic where simulation software has a great deal to say is HIL, Hardware In the Loop, or Real-Time Simulation [5].

When simulating a power plant performance, researchers can reasonably doubt about the dynamical response of the generator in the simulation model, compared to the real generator under study. This paper presents a validity study of the Matlab/Simulink Synchronous-Machine block for the use as generator in power-plant stability studies. This block belongs to SimPowerSystems Simulink Library, developed by Hydro-Québec.

Sudden short-circuit test is the most widely used method to calculate reactances and time constants of commercial alternators, and it permits to analyze electrical, magnetic and physical phenomena involved in transient periods [6], [7]. Therefore, this test is the one used to validate the dynamical performance of the Simulink block in this paper, by two different comparisons. First of all, the simulation model response is compared to the theoretical expressions of the synchronous generator currents when sudden short-circuiting its terminals. The second comparison matches the simulated behavior with real generator three-phase sudden short-circuit test records. Real data of three commercial synchronous generators are summarized in Appendix I.

II. SHORT-CIRCUIT CURRENTS COMPONENTS

As it is widely known, the three-phase short-circuit currents depend on the instant when the fault occurs. In Fig. 1, the short-circuit current of each phase are shown, as an example. Moreover, the field current during the fault is also represented (Fig. 1 (d)).

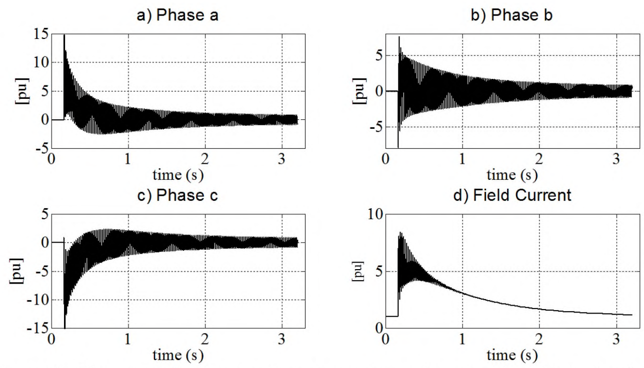

Figure 1. Phase and field currents during a three-phase sudden short-circuit.

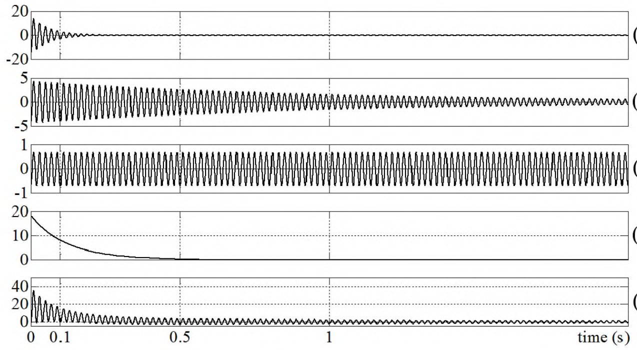

Figure 2. Short-circuit current components; (a) subtransient; (b) transient; (c) permanent; (d) DC; (e) short-circuit current.

Time evolution of each phase current can be explained as a continuous variation of the effective reactance through time. When analyzing this problem, a more feasible approach consists of dividing it in several different time periods, and considering a unique constant reactance for each period. Commonly, four components are considered: subtransient, transient, permanent and DC, as double frequency component is usually disregarded (Fig. 2). Because of the test conditions, rotor speed is considered constant; therefore equations of the general model become linear and can be solved by the superposition principle and Laplace transform as described in [8].

1. *Subtransient Component*: only appears in generators with damper windings. In the subtransient period the largest currents are reached. Its duration varies between 20 and 60 ms. Equation (1) represents the expression of this component:

$$i''_{ka}(t) = \sqrt{2}E_0 \cdot \left[\left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)\cdot \varepsilon^{-t/\tau''_d}\right] \sin(\omega t + \theta_0) \qquad (1)$$

2. *Transient Component*: transient period extends by 2 to 5 seconds, phase currents decrease as an exponential function (2) until they reach the permanent period value.

$$i'_{ka}(t) = \sqrt{2}E_0 \cdot \left[\left(\frac{1}{X'_d} - \frac{1}{X_d}\right)\cdot \varepsilon^{-t/\tau'_d}\right] \cdot \sin(\omega t + \theta_0) \qquad (2)$$

3. *Permanent Component:* also known as steady state component, its current value (3) is the result of the steady state operation of the generator with its three terminals short-circuited.

$$i_{ka0}(t) = \sqrt{2}E_0 \cdot \frac{1}{X_d} \cdot \sin(\omega t + \theta_0) \qquad (3)$$

4. *DC Component:* depending on the instant value of the phase voltage when the short circuit is applied, an asymmetric component appears, which diminishes as an exponential function (4). The DC component is strongly dependent on rotor saliency:

$$i_{kDC}(t) = -\frac{\sqrt{2}\cdot E_0}{2}\cdot\left(\frac{1}{X''_d} + \frac{1}{X''_q}\right)\cdot \varepsilon^{-t/\tau_a} \cdot \sin(\theta_0) \qquad (4)$$

5. *Double frequency Component:* the time-depending components described above origin a fixed axis magnetomotive force in the excitation winding, which creates a 100Hz current on stator windings. As X''_d and X''_q usually are similar, double frequency component (5) is commonly negligible.

$$i_{k\_2\omega}(t) = -\frac{\sqrt{2}\cdot E_0}{2}\cdot\left(\frac{1}{X''_d} - \frac{1}{X''_q}\right)\cdot \varepsilon^{-t/\tau_a} \cdot \sin(2\omega t + \theta_0) \qquad (5)$$

Where:

- E_0 is the generator voltage previous to short-circuit.
- θ_0 is the angle between phase "A" and the direct axis at the beginning of the transient.
- X''_q is the quadrature axis subtransient synchronous reactance.
- X_d, X'_d *and* X''_d are the direct, transient and subtransient direct synchronous reactances, respectively.
- τ'_d *and* τ''_d are short-circuit, transient and subtransient direct axis time constants.
- τ_a is the armature time constant.

Equation (6) shows phase "A" current waveform, addition of the five components described above. The symmetrical components of the other two currents are phase-shifted by 120 degrees from each other.

$$i_{ka} = i_{ka0} + i'_{ka} + i''_{ka} + i_{kDC} + i_{k\_2\omega} \qquad (6)$$

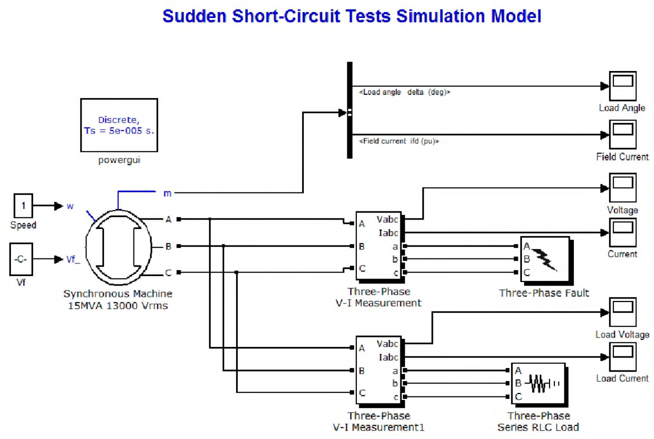

Figure 3. Simulation model used for sudden short-circuit simulations.

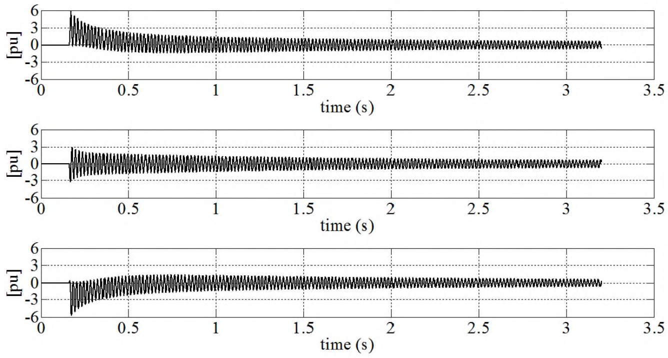

Figure 4. Sudden short-circuit currents calculated using theoretical equation. Hydro generator 29.35MVA, 10kV.

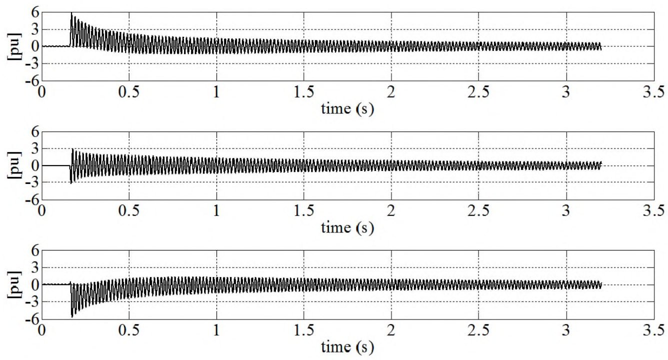

Figure 5. Sudden short-circuit currents from Matlab simulation. Hydro generator 29.35MVA, 10kV.

III. Comparison between Simulated and Theoretical Short-Circuit Currents

In this section, the synchronous generator theoretical response to a sudden short-circuit in its terminals is going to be compared to the synchronous machine block response in a similar situation (Fig. 3), using data from commercial generators.

Sudden short-circuit tests must be performed at rated speed [6], which is assumed to remain constant during the test. In order to prevent damages in the generator, the sudden short-

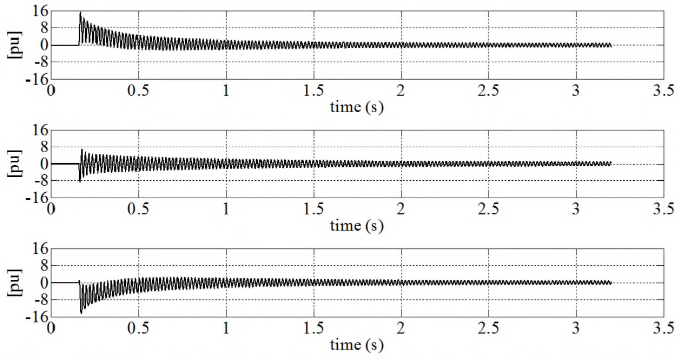

Figure 6. Sudden short-circuit currents calculated using theoretical equation. Turbo generator 75MVA, 11.5kV.

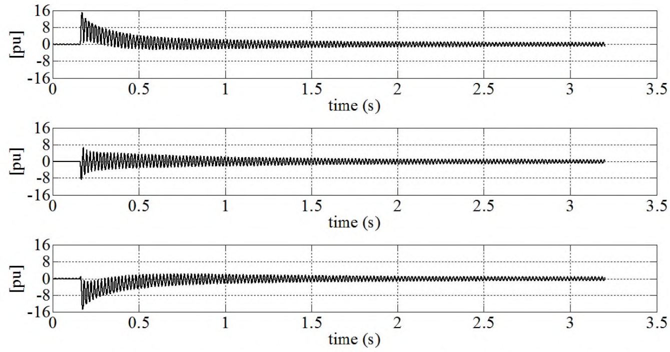

Figure 7. Sudden short-circuit currents from Matlab simulation. Turbo generator 75MVA, 11.5kV.

circuit tests are performed at reduced voltage. The simulation model shown in Fig. 3, implements this test in the Simulink environment, using blocks from SimPowerSystems library, which has been developed by Hydro-Québec.

The Synchronous Machine block response is the result of the interaction between two subsystems: the mechanical and the electrical ones. The mechanical subsystem of the machine is based on [9]. Model parameters should be set in order to operate at rated speed during the tests. The electrical subsystem is represented by a sixth-order state-space model in the rotor reference [10]. All rotor parameters and electrical quantities are viewed from the stator.

Sudden short-circuit tests must be performed with the machine operating on no-load conditions [6], [7]. Nevertheless, a low resistive three-phase load must be used in the simulation model, in order to avoid numerical oscillations and guarantee numerical stability of the solver method [11], [12] as the generator is modelled as a current source.

Two different simulations have been performed in this section, using data from real generators. The first data used come from Generator I (29.35MVA, 10kV), which is a 7 poles pairs salient rotor Hydro generator. The second data used for simulations come from a 75MVA, 11.5kV turbogenerator, Generator II, which is round rotor. Generator data are gathered on tables I and II on Appendix I.

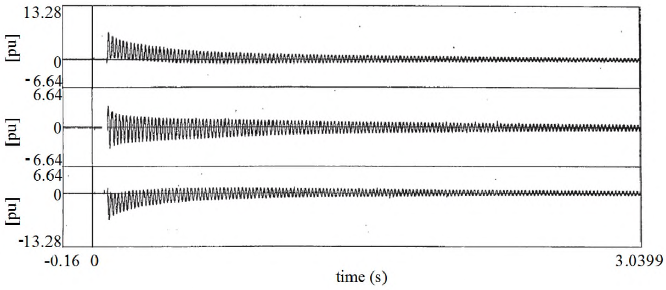

Figure 8. Sudden short-circuit currents during factory tests. Turbo generator 75MVA, 11.5kV.

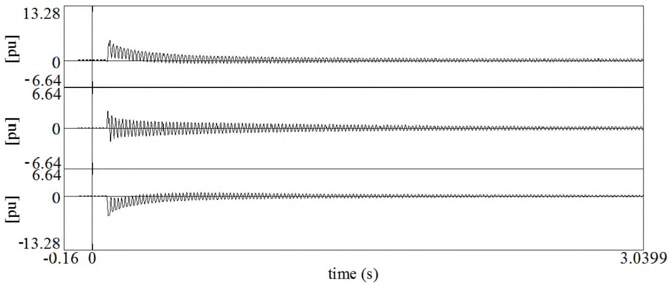

Figure 9. Sudden short-circuit currents from Matlab simulation. Turbo generator 75MVA, 11.5kV.

The choice of these synchronous machines is not random. Both generators differ on them rotor type, salient and round, and on them rated powers, 29.35MVA and 75MVA, respectively.

Fig. 4 shows the theoretical currents result of applying (6) with data from Generator I at 50% of rated voltage. Fig. 5 shows a sudden short-circuit test at 50% of rated voltage performed on the simulation model shown in Fig. 3, using Generator I data.

Fig. 6 shows the theoretical currents result of applying (6) with data from Generator II at rated voltage. Fig. 7 shows a sudden short-circuit test at rated voltage performed on the simulation model shown in Fig. 3, using Generator II data.

As observed in Fig. 4 to 7, there are not significant differences between the response of the generator block and the theoretical behavior expected, even considering different kinds of rotor and rated powers.

IV. Comparison between Simulated and Real sudden Short-Circuit Tests Currents

In this section, the Synchronous Machine block response is going to be compared to real generator records from sudden short-circuit tests.

Two different cases are treated: on one hand, using data from Generator II (table II, Appendix I) on the simulation

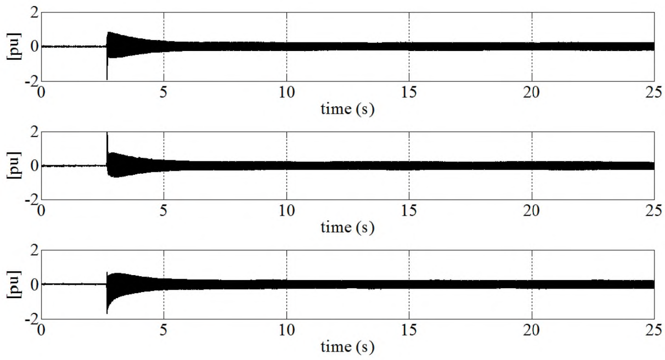

Figure 10. Sudden short-circuit currents during factory tests. Diesel generator 15MVA, 13kV.

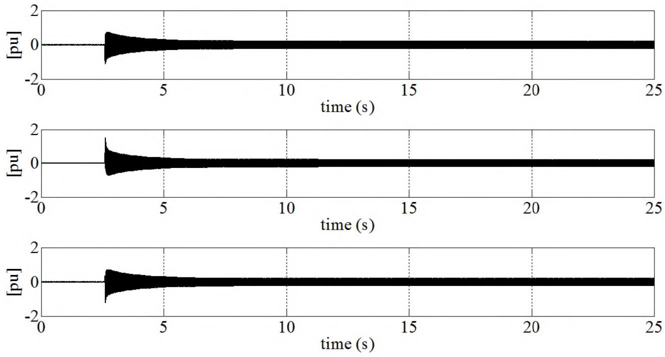

Figure 11. Sudden short-circuit currents from Matlab simulation. Diesel generator 15MVA, 13kV.

model, a sudden short-circuit test is emulated and compared to the real one. On the other hand, real sudden short-circuit currents are compared to the simulation ones for Generator III (table III, Appendix I). The entirety of the parameters used in this simulation has been calculated from real tests performed to Generator III [7], [13], [14].

Fig. 8 shows the three phase currents of the sudden short-circuit test record on Generator II. This test was performed at rated speed and reduced voltage (32.6% of rated voltage). Fig. 9 shows the currents obtained from the simulation model of Fig. 3, emulating the same test as in Fig. 8, using data from Generator II.

Comparison between Fig. 8 and 9 shows that the results through the simulation model are consistent with the factory sudden short-circuit test of Generator II.

Fig. 10 and 11 show a comparison between Generator III sudden short-circuit tests (31.9% of rated voltage, rated speed) and the currents output of the simulation model when emulating the same test. Synchronous reactances X_d, X'_d and X''_d, and time constants τ_a, τ'_d and τ''_d of this generator have been calculated as [2] establishes.

The larger differences on Fig. 10 and 11 (comparing to as Fig. 8 and 9 ones) are acceptable, because the parameters utilized in this simulation have been calculated from a record (with the errors that this operation carries). In spite of these variations, the dynamic response has proved to be adequate enough for power-plant real-time simulation.

V. CONCLUSIONS

The tests show that the SimPowerSystems Synchronous Machine block is able to reproduce the transient response of a real synchronous generator.

When comparing theoretical response with the simulation model response, as the tests summed up in Section III show, it can be seen that differences between both currents are negligible. When comparing the simulation model response with the real generator sudden short-circuit test records, as the tests summed up in the previous section show, it can be seen that there are not significant differences on the block behavior.

In view of all the results shown, it is right to conclude that, if generator data are available, they can be used for the setting of the simulation model parameters, and it represents faithfully the real generator behavior. On the contrary, if generator data are not available, they can be extracted from tests [2], and utilized in the model, in order to correctly simulate the generator transient behavior.

The simulation model described above based on SimPowerSystems library, and the synchronous machine block are suitable for simulations of power plants, and transient periods like short-circuits. Dynamic responses shall be practically identical to real power plants ones.

VI. APPENDIX I

TABLE I
GENERATOR I

SALIENT-POLE HYDRO GENERATOR			
Mag.	Value	*Mag.*	Value
Sn	29.35 MVA	X_l	0.172 pu
Un	10kV	R_s	0.00371 pu
p	7	τ'_d	1.611 s
X_d	1.826 pu	τ''_d	0.041 s
X'_d	0.351 pu	τ'_{d0}	9.049 s
X''_d	0.213 pu	τ''_{d0}	0.066 s
X_q	1.091 pu	τ''_{q0}	0.201 s
X''_q	0.223 pu	τ_a	0.187 s

TABLE II
GENERATOR II

ROUND-ROTOR TURBO GENERATOR			
Mag.	Value	*Mag.*	Value
Sn	75 MVA	X_l	0.108 pu
Un	11.5kV	R_s	0.0017 pu
p	1	τ'_d	0.890 s
X_d	2.042 pu	τ''_d	0.02 s
X'_d	0.192 pu	τ'_{d0}	9.470 s
X''_d	0.136 pu	τ''_{d0}	0.028 s
X_q	2 pu	τ''_{q0}	0.040 s
X''_q	0.120 pu	τ_a	0.180 s

TABLE III
GENERATOR III

SALIENT-POLE DIESEL GENERATOR			
Mag.	Value	*Mag.*	Value
Sn	15 MVA	X_l [b]	0.172 pu
Un	13kV	R_s [c]	0.0029 pu
p	3	τ'_d [a]	2.39278 s
X_d [a]	2.203 pu	τ''_d [a]	0.315 s
X'_d [a]	0.642 pu	τ'_{d0}	-
X''_d [a]	0.542 pu	τ''_{d0}	-
X_q [b]	1.3 pu	τ''_{q0}	-
X''_q [b]	0.350 pu	τ_a [a]	0.319 s

[a] Parameter calculated from sudden short-circuit test [2].

[b] Parameter estimated from similar generators.

[c] Parameter calculated as combination of some of the rest of them.